DEVELOPMENT AND APPLICATION OF GSTAR-1D

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Abstract: GSTAR-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. GSTAR-1D is able to compute water surface profiles in single channels, simple channel networks, and complex channel networks. It has both steady and unsteady flow models, many sediment transport equations, floodplain simulation, and cohesive and non-cohesive sediment transport. Lateral inflows can be simulated along with internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates. GSTAR-1D is applied to a reach of the Rio Grande, from Cochiti Dam to Isleta Diversion Dam from 1972 to 1992 and from 1992 to 2002. The bed profile and sediment cumulative erosion are compared with the field data. After calibration, the model is used to predict future sedimentation in the Cochiti Reach. The application demonstrates the capability of the model in solving practical river engineering problems.

1. INTRODUCTION

GSTAR-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. It is able to compute water surface profiles in single channels, dendritic, and looped network channels. It has both steady and unsteady flow models, steady and unsteady sediment models. GSTAR-1D uses standard step method to solve the energy equation for steady gradually varied flows. GSTAR-1D uses a modified "NewC" scheme to solve the de St Venant equations for unsteady rapid varied flows. Two methods of sediment transport are used in GSTAR-1D. For a long term simulation, the unsteady term of the sediment transport continuity equation are ignored, and the non-equilibrium sediment transport method of Han (1980) is used. For a short term simulations, the governing equation for sediment transport is the convection-diffusion equation with a source term arising from sediment erosion/deposition. This equation is solved with an implicit finite-volume method and with the Lax-Wendroff TVD scheme for the convective term and the central difference scheme for the diffusion term. Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates are simulated. The notation of an active layer, which allows selective erosion, provides an appropriate framework to simulate the bed armoring. Non-cohesive sediment transport equations and cohesive sediment physical processes are applied to calculate the sediment deposition and erosion. The most recent version can be downloaded at: *www.usbr.gov/pmts/sediment*.

GSTAR-1D is applied to the Cochiti Reach of the Middle Rio Grande, New Mexico to study channel geomorphic changes after the construction of the Cochiti Diversion Dam, and project future aggradations/degradation and streambed characteristics to assist river management. Successful management of the Middle Rio Grande relies a great deal on predicting changes in channel geometry, sediment transport, and river plan form while protecting and maintaining habitat for various operation and maintenance alternatives. The reduction of sediment supply to the Middle Rio Grande below Cochiti, Isleta, and San Acacia Dam has increased the recent trend of channel incision and narrowing. This incision and narrowing in the river causes the channel depth and velocity to increase. Thus, the river is providing fewer and fewer areas of good habitat for both the Rio Grande silvery minnow (RGSM) and southwestern willow flycatcher (SWFL). In many areas the river is coarsening from a sand bed to a gravel bed. The model is first calibrated with field measurements/data to two time periods: 1972 through 1992 and 1992 through 2002. Following calibration of the sediment transport model, an analysis of future sedimentation on the Middle Rio Grande is performed.

2. Numerical Model

2.1 <u>Hydraulic Model</u>

GSTAR-1D provides both steady and unsteady flow components to handle gradually varied flows and rapidly varied flows, in a simple channel or a complex channel network. GSTAR-1D uses standard step method to solve the energy equation for steady gradually varied flows. GSTAR-1D uses a modified "NewC" scheme to solve the de St Venant equations for unsteady rapid varied flows. Interested readers can refer to the GSTAR-1D user's manual for more details (Yang et al., 2004)

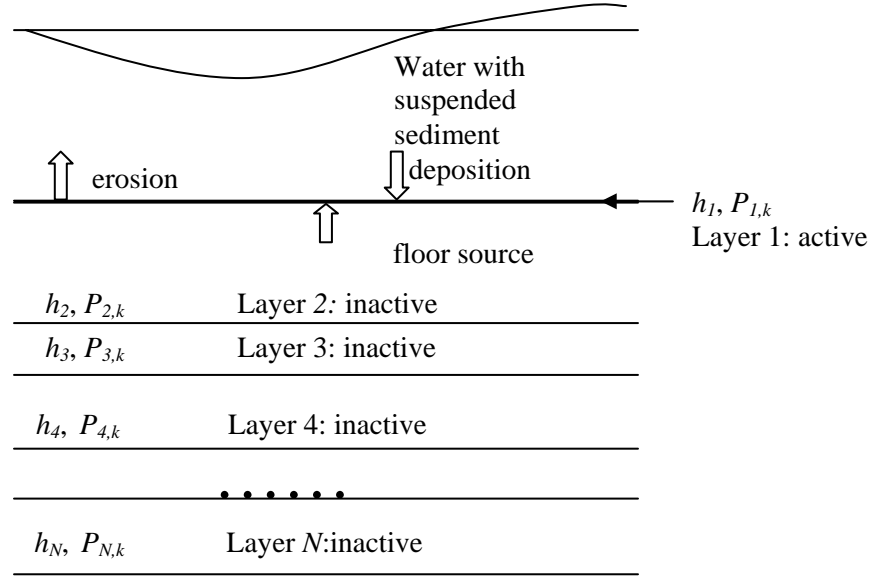### 2.2 <u>Sediment Transport Model</u>

Figure 1 Conceptual model

This section describes the conceptual model to simulate sediment transport in natural river systems. Figure 1 is a schematic of the conceptual model, in which the bed is composed of one active layer and N-1 inactive layers. In this figure, h_n = bed thickness of layer n, $P_{n,k}$ = volume fraction of k-th size class in layer n. The model is able to simulate both non-cohesive and cohesive sediment at the same time. A maximum of nf size fractions will be used to represent the sediment size distributions. The model includes cohesive sediment processes, such as settling, deposition, erosion, and consolidation. Consolidation of the sediment bed is modeled using multiple bed layers.

The bed profile is assumed to be composed of a number of layers of various thicknesses and bulk density. In each layer, bulk density of the cohesive sediment increases with time according to empirical consolidation rate, while the bulk density of the non-cohesive sediment remains constant. During consolidation, the bed thickness decreases but no mixing exists between layers.

The notation of an active layer provides an appropriate framework for erosion and deposition modeling. The active layer is defined as a thin upper layer bed of constant thickness, which is proportional to the geometric mean of the largest size class. The constant of proportionality is user defined. Each layer is assumed to have a uniform size distribution and bulk density throughout its depth. It is also assumed that all sediment particles of a given size class inside the active layer are equally exposed to the flow. Experimental results demonstrate that the presence of the fine cohesive sediment in the bed can increase the bed's resistance to erosion. The model used by GSTAR-1D assumes that the erosion rates of silts, sands and gravels are limited by the entrainment rate of the clay if the fraction of clay is above a user specified value.

The notation of an active layer allows size specific erosion on the streambed surface. If the bed shear stress is larger than the critical shear stress for the finer size classes, but smaller than that for coarser size classes, only the finer size classes are eroded. This process of selective erosion will eventually armor the bed surface and prevent further erosion.

The active layer contains the bed material available for transport. During net erosion, the first inactive layer supplies material to the active layer. During net deposition, the additional material is moved to the first inactive layer. A range is set for the thickness of the first inactive layer. The lower limit is set to allow enough sediment to be supplied to the active layer during erosion. The upper limit is set to provide enough resolution of the layers when simulating the bed layer. When it becomes very thin during net erosion, it merges with the second inactive layer. On the other hand, when it becomes very thick during net deposition, it is divided into two layers. All other layers are shifted accordingly.

Two kinds of sediment transport are introduced in GSTAR-1D. For a long term simulation, the unsteady term of the suspended sediment transport continuity equation are ignored. In this method, GSTAR-1D uses the non-equilibrium sediment transport method of Han (1980). For a short term simulations, the governing equation for sediment transport is the convection-diffusion equation with a source term from sediment erosion/deposition. This equation is solved with an implicit finite-volume method. The Lax-Wendroff TVD scheme is used to discretize the convective term. A central difference scheme is used to discretize the diffusion term.

Both non-cohesive and cohesive sediment can be simulated in GSTAR-1D. GSTAR-1D employs 13 transport functions for non-cohesive sediment transport. Cohesive sediment transport is controlled by user-specified parameters that control the processes of aggregation, deposition, erosion, and consolidation.

GSTAR-1D calculates channel geometry adjustments in two ways: vertical change and width change. A vertical change adjusts the bed geometry under water uniformly. A width change adjusts the bed geometry under water surface linearly according to the local water depth. During a width adjustment, the maximum bed geometry adjustment occurs near the bank. In this way, the channel width is changed without thaweg elevation changing. Whether the adjustment will proceed in the depth or width direction at a given time step of computation depends on a user-specified minimization theory. However, in most cases simulated to date, the width adjustment option has not been used.

3. Numerical Model

3.1 Model Input

The simulations use the original 1972, 1992, and 2002 measured cross section data, average bed material gradation data at cross sections where data were available, daily flow data at Cochiti Diversion Dam, and calibrated Manning's coefficient values for the main channel and the floodplains. After the closure of the Cochiti Diversion Dam, the reservoir trapped more than 99% of the sediment incoming. The model assumes that no sediment incoming from upstream boundary at the Cochiti Diversion Dam. The sediment yield from an ungaged tributary is estimated from the hydrology data and the related watershed. The sediment yield from a gaged tributary is estimated from the Modified Einstein Procedure (Colby and Hembree 1955), which employs the measured suspended sediment concentrations, the bed material particle size distribution, and the measured hydraulic parameters to arrive at a total sediment load. The study reach ends at the Isleta Diversion Dam, where water surface elevations are used as the downstream boundary condition. The model consists of 133 cross sections starting at the Cochiti Diversion Dam and ending at the Isleta Diversion Dam.

3.2 1992-2002 model calibration

The numerical model reproduces the general shape and magnitude of the cumulative erosion and deposition in the main channel (Figure 2). From Cochiti Diversion Dam to Angostura Diversion Dam, the field measurements show that the main channel were in state of dynamic equilibrium and experienced minimal erosion and deposition. The numerical model reproduces the same trend, but predicts that there was slight aggradation from Tonque Arroyo to Angostura Diversion Dam. From Angostura Diversion Dam to Arroyo de la Baranca, the field measurements show that the main channel experienced erosion. The numerical model reproduces the same trend. From Arroyo de la Baranca to Isleta Diversion Dam, the field measurements show that the main channel experienced no erosion or deposition. The model predicts that there was slight erosion from Arroyo de la Baranca to 10km downstream of

Arroyo de las Calabacillas and no erosion and deposition downstream. It should be mentioned that the original model predicted erosion in this reach so the bed material was intentionally coarsened in this reach. In reality, the channel maintain relative equilibrium even though the surface bed material was fine in 1992.. This relative equilibrium was due to a variety of factors. Firstly, coarse sediments from the tributaries were deposited at their confluence with the Rio Grande. These coarse sediments might be moved to the thalweg due to transverse movement of sediment and provided material for the armored layer to prevent further erosion. These circumstances can not be simulated by a 1D model. Secondly, the bed material samples were usually collected in the falling stage of the flood and sand was deposited on the bed, thus, in many case the coarse sediment controlling the form of the channel could be covered by a finer layer of sand.. The bed was coarsened to reflect the coarser gradation that was assumed to form the channel.
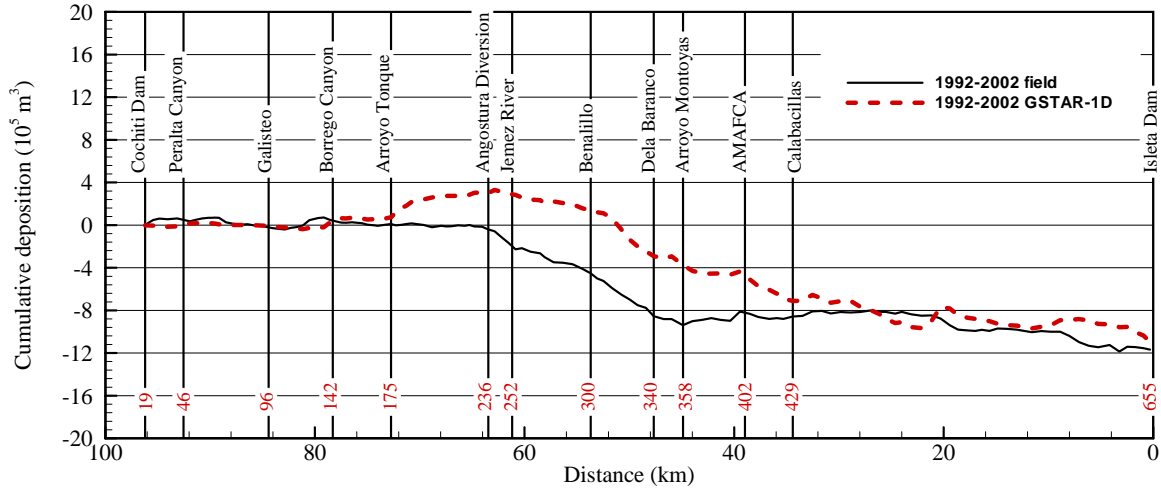

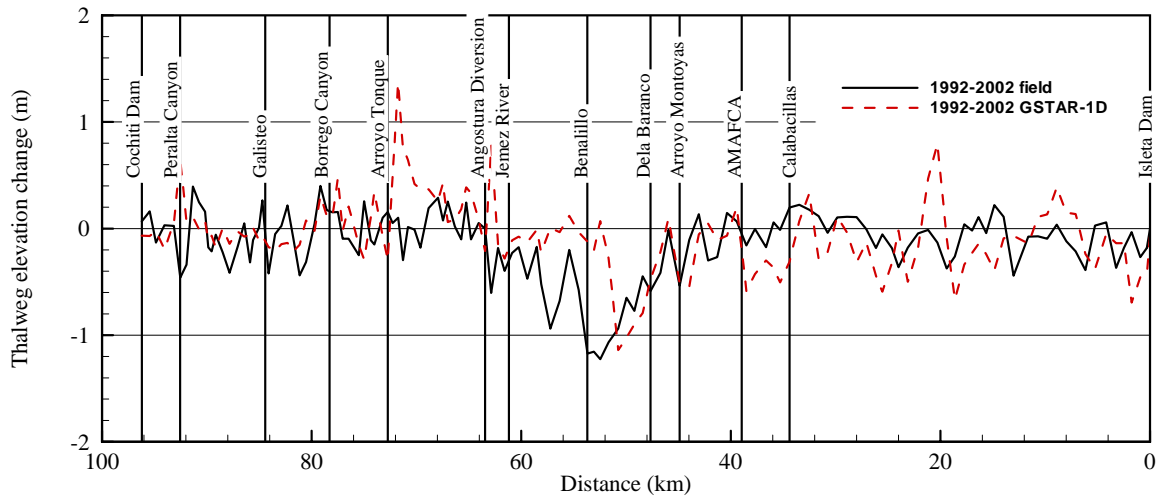Figure 2. Cumulative total volume of sediment from 1992 to 2002

Figure 3. 1992-2002 thalweg change

Figure 3 show the changes in thalweg profile from 1992 to 2002. Overall, the numerical model reproduces the thalweg profile change well. The bed elevations were stable upstream of Angostura Diversion Dam and are simulated fairly accurately, however, the model overpredicts aggregation downstream of the Tonque Arroyo due to lateral sediment input from the arroyo. The model predicts the degradation correctly from Angostura Diversion Dam to Arroyo de los Montoyas. The reach from Arroyo de los Montoyas to Isleta Diversion Dam was relatively stable with a little degradation, which is predicted by the model.
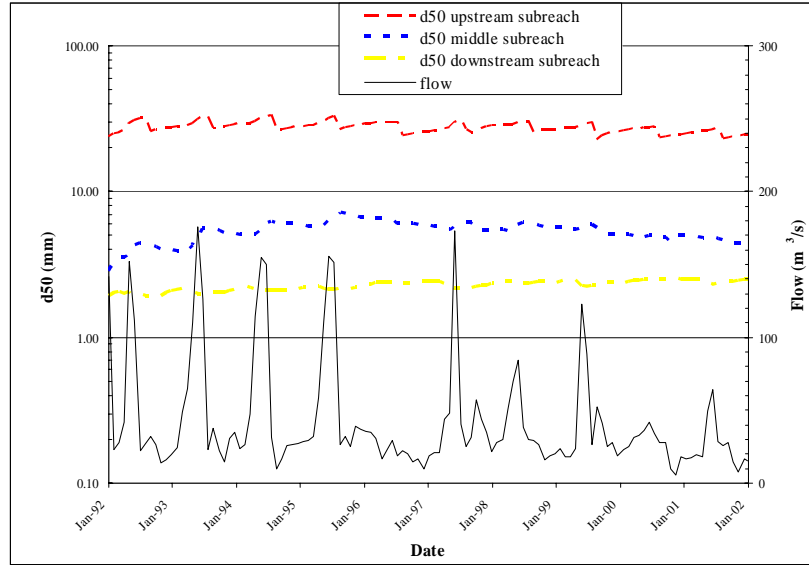
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Figure 4. Change in bed material size (d_{50}) during model simulation from 1992 to 2002

The median bed material size, d_{50}, of three subreaches is shown in Figure 4. The three subreaches are from Cochiti Dam to Angostura Diversion Dam, from Angostura Diversion Dam to Arroyo de los Montoyas, and from Arroyo de los Montoyas to Isleta Dam, respectively. In all three subreaches, the model results show the bed material became coarser during high flows and finer during low flows. In the first subreach from the Cochiti Dam to Angostura Diversion Dam, the bed material was coarse. Numerical results show that this reach had already reached approximate equilibrium with the upstream sediment supply and the d_{50} was relatively stable and in the range of coarse gravel. In the second subreach from Angostura Diversion Dam to Arroyo de los Montoyas, the median sediment size, d_{50}, was in the range of very fine gravel and fine gravel. The bed material tended to coarsen during a series of floods between 1992 and 1995 and then became a little finer thereafter. In the 10-year period the bed material (d_{50}) coarsened from 2.85 mm in 1992 to 4.36 mm in 2002. In the subreach from Arroyo de los Montoyas to Isleta Diversion Dam, the bed material was fine. Numerical results show that bed material was fine and was relatively stable. The mean bed material (d_{50}) in this reach was in the range of very fine gravel and showed a slow coarsening trend.

3.3 1972-1992 model calibration

The sediment transport from 1972 to 1992 was also simulated with only the river geometry and bed material fractions different and results are compared with the field data. Here only the change in bed material is presented in Figure 5 . In the reach from Angostura Diversion Dam to Arroyo de los Montoyas, the bed was coarsening from a sand-bed to a gravel bed. The numerical model shows that the median sediment size, d_{50}, changed from 0.7mm (coarse sand) to 3.8mm (very fine gravel), which is close to the field data of 4.3 mm measured in 1992. The model captures the coarsening of the bed material in whole Cochiti Reach after the closure of the Cochiti Diversion Dam in 1973. The model also reproduced the transition from a sand bed to a gravel bed in the reach from Angostura Diversion Dam to Arroyo de los Montoyas.
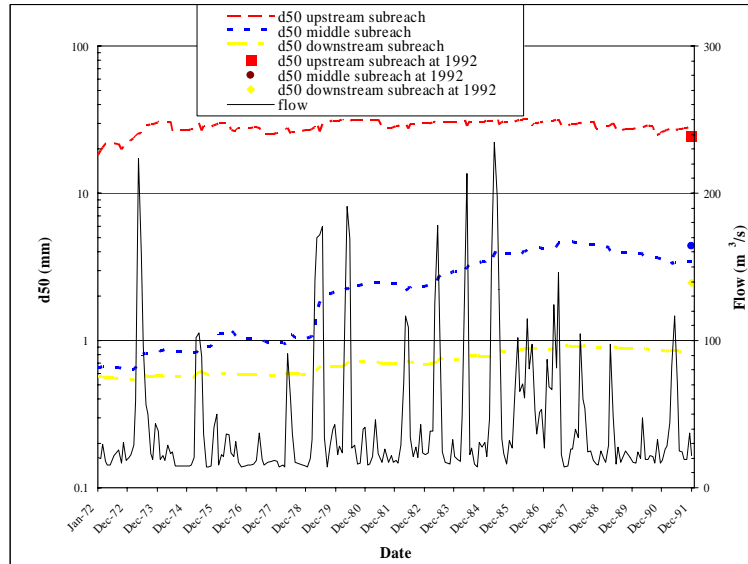
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Figure 5. Change in median bed material size (d_{50}) during model simulation from 1972-1992

3.4 2002-20222 prediction

After the model was calibrated using the period from 1972 to 1992 and from 1992 to 2002, the calibrated parameters are used for the 2002 to 2022 predictive model. The model uses 2002 cross-section data and the sediment bed gradation calculated from the end time of the 1992-2002 simulation. The predictive hydrology is based on the historical record of the San Felipe gage, which has the longest data in the reach. Three hydrologic scenarios were simulated: a dry, average, and wet hydrology . The water surface elevation at Isleta Diversion Dam, which is the downstream boundary condition for the model, is calculated according to the predictive hydrology.
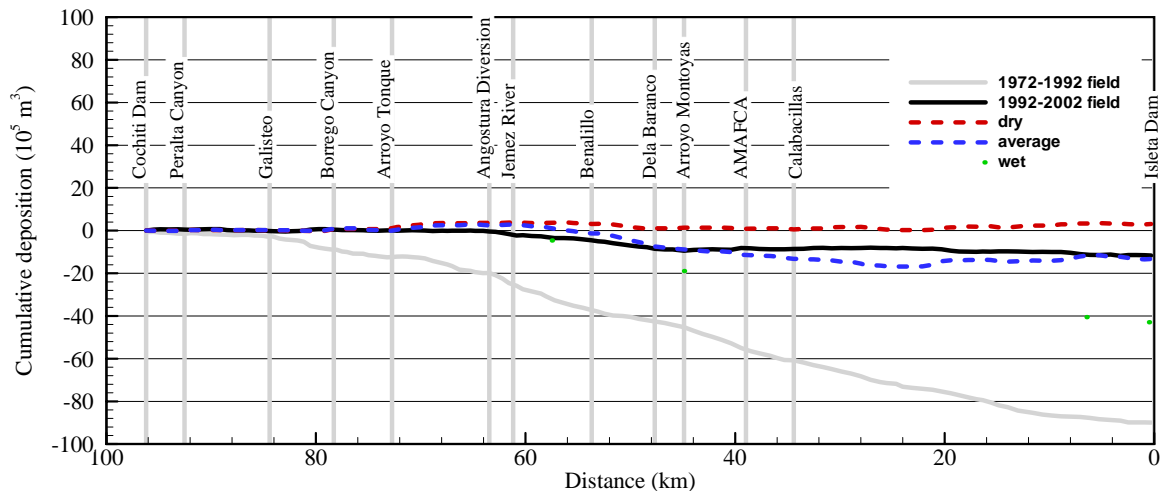

Figure 6. Cumulative main channel volume of sediment 2002-2022

Figure 6 shows the cumulative erosion in the main channel for the three different hydrological scenarios. The results show the erosion for the entire reach is similar to that of the historic record from 1992 to 2022. However, the erosion zone has moved slightly downstream. From the Cochiti Diversion Dam to Benalillo, the field measurements show that the main channel will be in an equilibrium state and experience only small amounts of erosion. The main

channel volume calculations are dependent upon the hydrology. As the dry hydrology causes essentially slight deposition while the wet hydrology causes the most erosion.
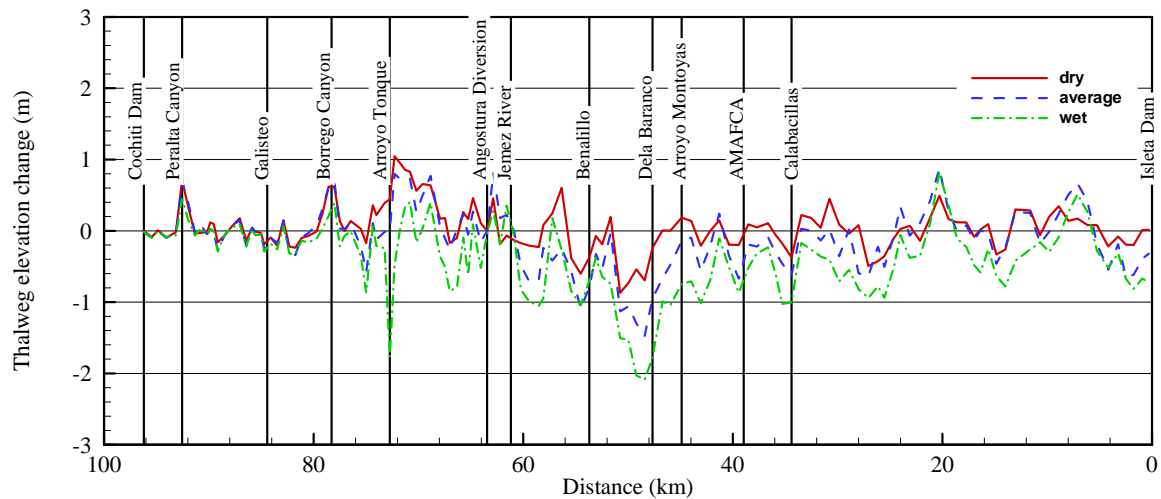

Figure 7. 2002-2022 change in thalweg

Figure 7 show the total changes in thalweg elevation, from the start (2002) of the simulation to the end (2022) for each hydrology. Overall, the bed elevations will be stable upstream of the Angostura Diversion Dam with slight sediment deposition at the confluences of Borrego Canyon for all hydrologies and erosion upstream of the confluences of Tonque Arroyo during the wet hydrology. Degradation is predicted for a 18 km reach beginning at the confluence of the Jemez River.

Table 1 summarizes the reach-averaged median sediment size, d_{50}, at the beginning and end of the simulation. The bed material becomes coarser in all three subreaches and in all hydrologies. The bed material will encounter greatest coarsening during wet hydrology.

Table 1. Reach-averaged median sediment size d_{50} at the beginning and end of the simulation

	d_{50} (mm) at year 2002	d_{50} (mm) at year 2022		
		Dry	Average	Wet
upstream subreach	22.55	25.66	26.44	33.56
middle subreach	4.18	4.58	8.24	9.64
downstream subreach	2.10	2.32	2.67	3.36

4. Summary

The GSTAR-1D model is briefly presented in this paper. GSTAR-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. GSTAR-1D can be used to simulate flows in simple channels and in channel networks, to simulate steady and unsteady flow and sediment transport, and to simulate cohesive and non-cohesive sediment transport.

GSTAR-1D was used to simulate the channel and bed material changes of the Middle Rio Grande from the Cochiti Diversion Dam to Isleta Diversion Dam. The model was calibrated with the data from two time periods; 1972 through 1991 and 1992 through 2001. These two periods covered typical dry and wet hydrologic conditions. From the calibration results it was found that the modified GSTAR-1D model was capable of reproducing the river geometry changes and bed material coarsening caused by the reduced sediment supply. After the model was

calibrated for these two time periods, the model was used to predict future sedimentation for various hydrologic regimes: dry, average, and wet.

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